Measurements of the Total and Differential Higgs Boson Production Cross Sections Combining the H -> gamma gamma and H -> ZZ* -> 4l Decay Channels at root s=8 TeV with the ATLAS Detector

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Measurements of the Total and Differential Higgs Boson Production Cross Sections Combining the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ Decay Channels at $\sqrt{s} = 8$ TeV with the ATLAS Detector

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Measurements of the total and differential cross sections of Higgs boson production are performed using 20.3 fb^{-1} of pp collisions produced by the Large Hadron Collider at a center-of-mass energy of $\sqrt{s} = 8$ TeV and recorded by the ATLAS detector. Cross sections are obtained from measured $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ event yields, which are combined accounting for detector efficiencies, fiducial acceptances, and branching fractions. Differential cross sections are reported as a function of Higgs boson transverse momentum, Higgs boson rapidity, number of jets in the event, and transverse momentum of the leading jet. The total production cross section is determined to be $\sigma_{pp\to H} = 33.0 \pm 5.3\,(\mathrm{stat}) \pm 1.6\,(\mathrm{syst})$ pb. The measurements are compared to state-of-the-art predictions.

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This Letter presents measurements of the total and differential cross sections of inclusive Higgs boson production using 20.3 fb^{-1} of pp collisions produced by the Large Hadron Collider (LHC) [1] at a center-of-mass energy of $\sqrt{s} = 8$ TeV and recorded by the ATLAS detector [2]. The measured cross sections probe the properties of the Higgs boson and can be directly compared to the theoretical modeling of different Higgs boson production mechanisms, such as the most recent gluon fusion (ggF) QCD calculations. They can also be used to constrain new physics scenarios, for example using the effective field theory framework as proposed in Refs. [3–7]. The analysis uses event yields measured in the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ decays and detector efficiencies, both determined as described in Refs. [8,9]. The statistical uncertainties on the Higgs boson signal yields in both channels are larger than the systematic uncertainties, while the total uncertainties in the two channels are similar. Combining the analyses improves the precision of the cross-section measurements by up to 40%, and by 25%–30% on average, with respect to the corresponding measurements in the most precise individual channel.

Distributions of the differential $pp \to H$ cross sections are reported as a function of the transverse momentum $p_{\mathrm{T}}^{\mathrm{H}}$ and the rapidity $|y^{\mathrm{H}}|$ of the Higgs boson, the jet multiplicity N_{jets}, and the transverse momentum of the leading jet $p_{\mathrm{T}}^{\mathrm{j1}}$. The observables $p_{\mathrm{T}}^{\mathrm{H}}$ and $|y^{\mathrm{H}}|$ describe the kinematics of the Higgs boson. They are sensitive to perturbative QCD modeling in ggF production, which is the dominant Higgs boson production mechanism in the Standard Model (SM). The $|y^{\mathrm{H}}|$ distribution furthermore offers a clean probe of the gluon parton distribution function (PDF) and will play a role in future PDF fits. The N_{jets} and $p_{\mathrm{T}}^{\mathrm{j1}}$ observables probe the theoretical modeling of partonic radiation in ggF production as well as the overall rate and modeling of jets in vector-boson fusion (VBF) and associated Higgs boson production (VH and $t\bar{t}H$). Jets produced in VBF, VH, and $t\bar{t}H$ processes tend to have higher transverse momenta than those produced via ggF production; however, the sensitivity to measuring these contributions is weak with the current amount of data.

Cross sections are extracted using a combined likelihood built from the signal yields in the $H \to \gamma\gamma$ channel and the data and background yields in the $H \to ZZ^* \to 4\ell$ channel, as well as detector efficiencies, fiducial acceptances and SM branching fractions [10]. A complementary approach, using a separate likelihood, measures the shape of the differential distributions by imposing a unity normalization constraint, which removes the implicit SM assumption on the branching fractions. For the extraction of the signal yields and the corrections of detector efficiencies, it is assumed that the signal in both channels is due to a narrow resonance with a mass $m_H = 125.36 \pm 0.41$ GeV as measured by the ATLAS Collaboration [11]. The signal yield in the $H \to \gamma\gamma$ channel is obtained from fits to the diphoton mass spectra [8], and from the background subtracted data yield in a $m_{4\ell}$ mass window of 118 to 129 GeV for the $H \to ZZ^* \to 4\ell$ channel [9]. The fiducial acceptance in both channels [8,9] is derived using a set of Monte Carlo (MC) event generators. POWHEG-BOX [12–14], interfaced with PYTHIA8 [15] for showering, is used to generate ggF and VBF events, while PYTHIA8 is used to simulate VH and

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associated production with top quarks ($t\bar{t}H$) and b-quarks ($b\bar{b}H$). The fiducial acceptance for events with $|y^{\mathrm{H}}| < 1.2$ is approximately 72% for $H \to \gamma\gamma$, and 55%–59% for $H \to ZZ^* \to 4\ell$. For higher $|y^{\mathrm{H}}|$, the acceptance decreases to 35%–38% in both channels. The fiducial acceptance is more constant as a function of the other variables and is in the range 56%–62% for the $H \to \gamma\gamma$ channel and 44%–53% for the $H \to ZZ^* \to 4\ell$ channel [16].

After correcting the differential cross sections and normalized shapes for fiducial acceptance and branching fractions, the corresponding measurements in both channels are found to be in good agreement with each other; p values obtained from χ^2 compatibility tests are in the range 56%–99% [16].

In the binned maximum-likelihood fit, the statistical uncertainty of the $H \to \gamma\gamma$ event yield is modeled using a Gaussian distribution, while the event yield in the $H \to ZZ^* \to 4\ell$ channel follows a Poisson distribution due to the small sample size. Experimental and theoretical systematic uncertainties affecting the signal yields, detector efficiencies, branching fractions, and fiducial acceptance corrections are taken into account in the likelihood as constrained nuisance parameters. Nuisance parameters describing the same uncertainty sources are treated as fully correlated between bins and channels. Systematic uncertainties on the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ background estimates and efficiency correction factors, as well as the uncertainty on the integrated luminosity, are described in detail in Refs. [8,9]. The branching fraction uncertainty due to the assumed quark masses and other theoretical uncertainties are evaluated following the recommendations of Ref. [17], considering uncertainty correlations between the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ decay channels. Uncertainties on the acceptance correction related to the choice of PDF set are evaluated by taking the envelope of the sum in quadratures of eigenvector variations of the baseline (CT10 [18]) and the central values of alternative (MSTW2008NLO [19] and NNPDF2.3 [20]) PDF sets. Uncertainties on the acceptance correction associated with missing higher-order corrections are evaluated by varying the renormalization and factorization scales coherently and individually by factors of 0.5 and 2 from their nominal values, and by reweighting the $p_{\mathrm{T}}^{\mathrm{H}}$ distribution from POWHEG-BOX to the prediction of the HRES 2.2 calculation [21,22]. The envelope of the maximum deviation of the combined scale variations and the $p_{\mathrm{T}}^{\mathrm{H}}$ reweighting is used as the systematic variation. To account for the uncertainty in the mass measurement, the Higgs boson mass is varied by ± 0.4 GeV. To assess the systematic uncertainty due to the assumption of SM cross-section fractions of the Higgs boson production modes, the VBF and VH fractions are varied by factors of 0.5 and 2 from the SM prediction and the fraction of $t\bar{t}H$ is varied by factors of 0 and 5. These factors are based on current experimental bounds [23–27].

The total uncertainties on the acceptance correction range from 1% to 6%, depending on the channel, distribution and bin.

The total systematic uncertainties on the combined differential cross sections range from 4% to 12%, depending on the distribution and bin. For the kinematic variables $p_{\mathrm{T}}^{\mathrm{H}}$ and $|y^{\mathrm{H}}|$, the largest systematic uncertainties on the differential cross sections are due to the luminosity and the background estimates in both channels. For the jet variables N_{jets} and $p_{\mathrm{T}}^{\mathrm{j1}}$, the largest systematic uncertainties on the differential cross sections are due to the jet energy scale and resolution. In the shape combination, the normalization uncertainties including luminosity, branching fractions, and efficiency uncertainties do not apply. Statistical uncertainties dominate all resulting distributions, ranging from 23% to 75%.

The total $pp \to H$ cross section is determined in the $H \to \gamma\gamma$ channel to be $31.4 \pm 7.2\,(\mathrm{stat}) \pm 1.6\,(\mathrm{syst})$ pb and in the $H \to ZZ^* \to 4\ell$ channel to be $35.0 \pm 8.4(\mathrm{stat}) \pm 1.8(\mathrm{syst})$ pb. Combining the analyses yields $\sigma_{pp\to H} = 33.0 \pm 5.3\,(\mathrm{stat}) \pm 1.6\,(\mathrm{syst})$ pb. Figure 1 presents a comparison of these measurements with two ggF predictions to which contributions from other relevant Higgs boson production modes (VBF, VH, $t\bar{t}H$, $b\bar{b}H$) are added using cross sections and uncertainties from Ref. [10]. The LHC-XS ggF prediction, recommended in Ref. [10], is accurate to next-to-next-to-leading order (NNLO) in QCD and utilizes threshold resummation accurate to next-to-next-to-leading logarithms (NNLL). A significant effort has been undertaken by the theory community to provide ggF cross sections beyond this precision through various improvements in the perturbative calculations [28–33]. Recently, the ADDFGHLM group has provided a fixed-order calculation accurate to next-to-next-to-next-leading order ($\mathrm{N^3LO}$) [34–37]. A PDF uncertainty

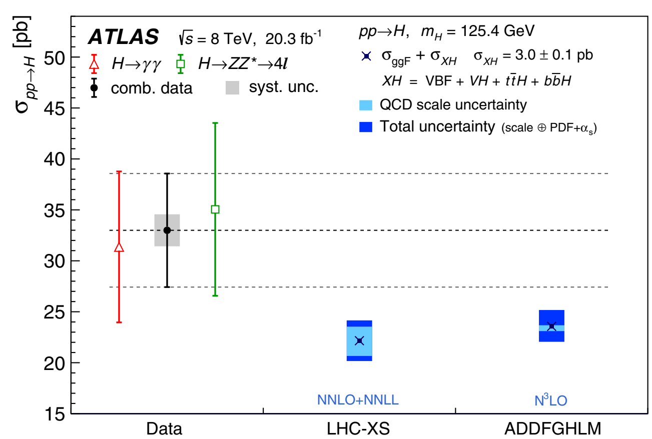

FIG. 1 (color online). Measured total cross section of Higgs boson production compared to two calculations of the ggF cross section. Contributions from other relevant Higgs boson production modes (VBF, VH, $t\bar{t}H$, $b\bar{b}H$) are added using cross sections and uncertainties from Ref. [10]. Details of the predictions are presented in Table I.

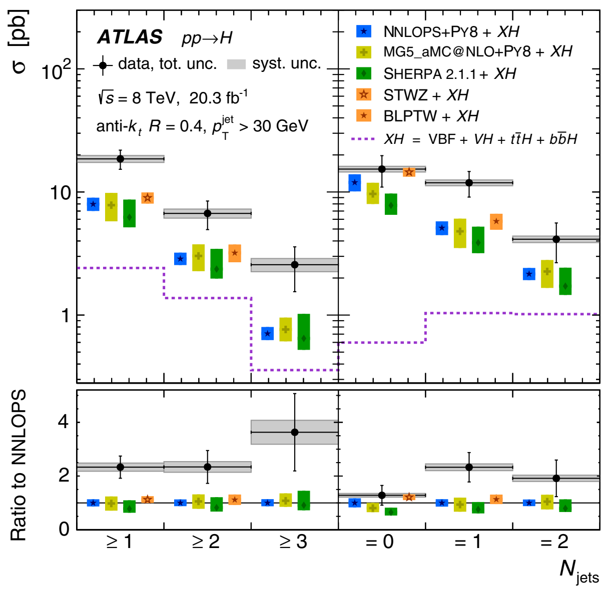

FIG. 2 (color online). Measured Higgs boson production cross sections in inclusive and exclusive jet multiplicity bins compared to different theoretical predictions (see Table I for details and references).

of $^{+7.5}_{-6.9}\%$ is assigned to the LHC-XS prediction, derived following the recommendations in Ref. [17]. This uncertainty is increased by $^{+0.3}_{-0.1}\%$ for the ADDFGHLM prediction corresponding to the change in uncertainty of the MSTW2008nnlo PDF set when changing the calculation from NNLO to N^{3}LO. The PDF uncertainty is treated as uncorrelated with the QCD scale uncertainty.

The central value of the measured total cross section is larger than the SM predictions presented in Fig. 1. A likelihood-ratio test statistic is used to quantify the agreement, using a bifurcated Gaussian to model the asymmetric theory uncertainties. The resulting p values are 5.5% and 9.0% for the agreement between data and the predictions from LHC-XS and ADDFGHLM, respectively. The ratio of the measured cross section to the LHC-XS prediction is higher than the results presented in Refs. [23,24,38], which use an event categorization based on the expected SM yields in the different Higgs boson production modes.

The larger Higgs event yield observed in data motivates measurements of differential cross sections to investigate if the excess is localized to specific kinematic regions. Figure 2 shows the comparison of the combined cross sections in different inclusive and exclusive jet multiplicity bins with state-of-the-art predictions, including NLO-accurate multi-leg (ML) merged ggF MC event generators (further details are given in Table I). Jets are reconstructed using the anti-k_t algorithm [39] with a radius parameter $R = 0.4$ [40], and are required to have $p_T > 30$ GeV and $|y| < 4.4$. Simulated particle-level jets are built from all particles with $c\tau > 10$ mm excluding neutrinos, electrons, and muons that do not originate from hadronic decays.

TABLE I. Summary of the ggF predictions used in the comparison with the measured cross sections. The second column states the order in QCD perturbation theory and which threshold resummation is applied, if any. Further details are provided in the footnotes. All predictions are for $m_H = 125.4$ GeV and $\sqrt{s} = 8$ TeV.

Total cross-section calculations	
LHC-XS [10]	NNLO + NNLL^{a,b,c}
ADDFGHLM [34–37]	N^{3}LO^{a,b,c}
Analytical differential cross-section predictions	
HRes 2.2 [21,22]	NNLO + NNLL^{a,e,f}
STWZ [28], BLPTW [45]	NNLO + NNLL^{c,d,e,g,h}
JetVHeto 2.0 [46–48]	NNLO + NNLL^{a,c,e}
Monte Carlo event generators	
SHERPA 2.1.1 [49,50]	$H + 0, 1, 2$ jets @NLO^{i,j}
MG5_aMC@NLO [51,52]	$H + 0, 1, 2$ jets @NLO^{i,k,l}
Powheg Nnlops [53,54]	NNLO$_{\geq 0j}$, NLO$_{\geq 1j}$^{e,l,m}

[a] Considers b- (and c-) quark masses in the $gg \to H$ loop.
[b] Includes electroweak corrections.
[c] Based on MSTW2008nnlo [19] (α_s from PDF set).
[d] Uses π^2-resummed $gg \to H$ form factor.
[e] NNLO refers to the total cross section.
[f] Based on the CT10nnlo PDF set.
[g] In the notation of Ref. [28], this corresponds to NNLL′.
[h] Includes 1-jet resummation included at NLL′ + NLO.
[i] Based on the CT10nlo PDF set.
[j] Uses MEPS@NLO method and CKKW merging scheme [55–57].
[k] Software version 2.2.1, NLO merged using FxFx scheme [52].
[l] Interfaced with Pythia8 for parton showering.
[m] Uses Minlo method and y^H reweighting to HNNLO [54,58,59].

Photons are excluded from jet-finding if they lie inside a cone of radius $\Delta R < 0.1$ of an electron or muon, and neither the photon nor lepton originate from a hadron decay. To allow comparisons with the unfolded measurements, the analytical calculations are corrected for effects of hadronization and multiple particle interactions. These correction factors and their associated uncertainties are obtained using the Pythia8 and Herwig [41] MC event generators with different tunes [42–44]. The total cross sections from the ML merged predictions are lower than from fully inclusive NNLO + NNLL calculations. However, for $N_{\rm jets} \geq 1$, the MC predictions formally have NLO accuracy, which is the same as the analytical calculations. Contributions from other relevant Higgs boson production modes are generated using Powheg for VBF and Pythia8 for VH, $t\bar{t}H$, and $b\bar{b}H$, and are scaled to the cross sections in Ref. [10]. Uncertainties are assigned to all MC predictions from QCD scale and PDF variations. The ML-merged ggF predictions also have uncertainties due to the choice of merging scale. The SHERPA uncertainties further include resummation scale variations. The measured cross sections are higher than the predictions for all measured jet multiplicities. The poorest

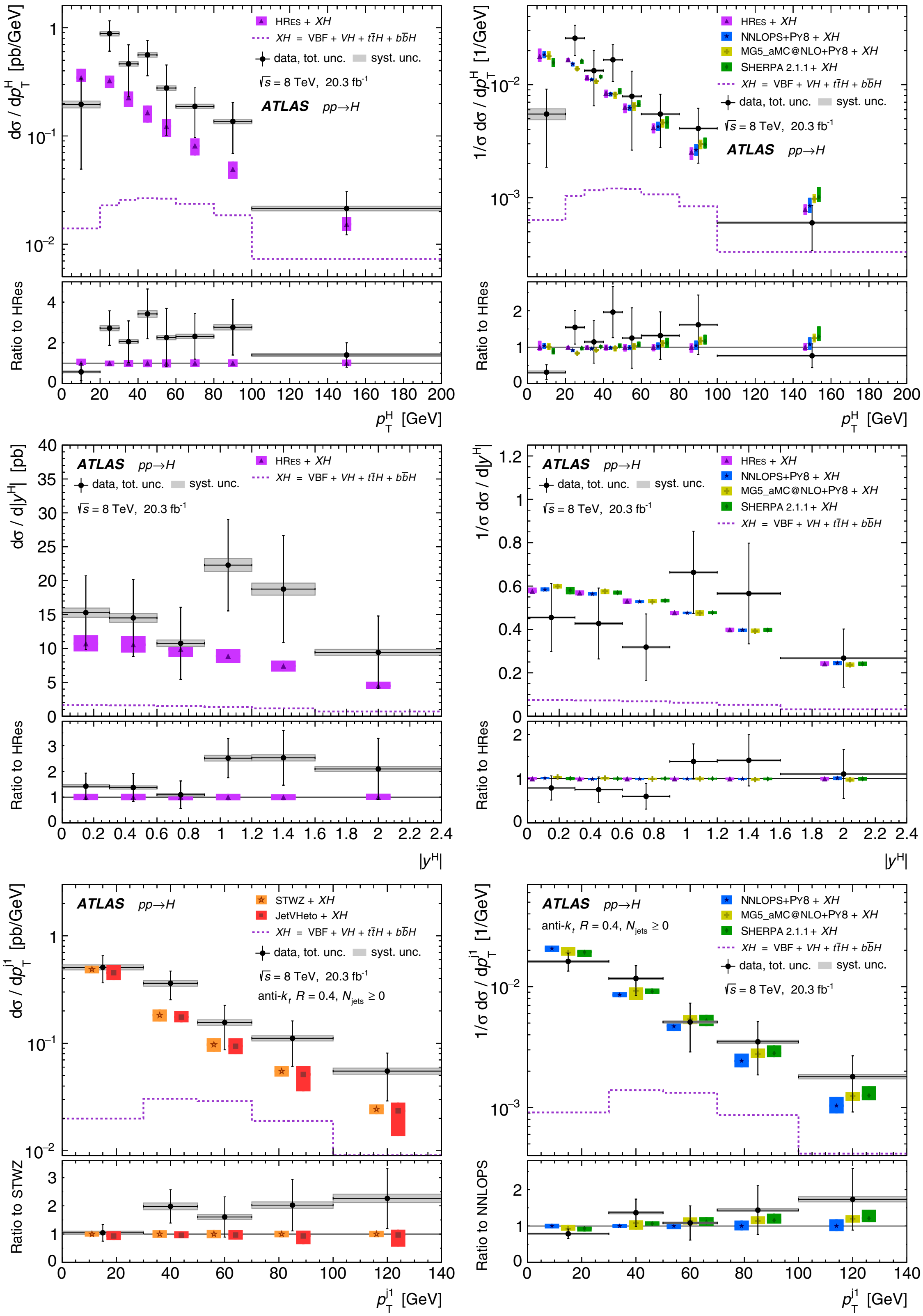

FIG. 3 (color online). Differential cross sections (left) and normalized cross-section shapes (right) for inclusive Higgs boson production measured by combining the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ channels. The measured variables are the Higgs boson transverse momentum p_T^H (top) and its rapidity $|y^H|$ (middle), and the transverse momentum of the leading jet p_T^{j1} (bottom). The 0–30 GeV bin of the p_T^{j1} distributions corresponds to events without jets above 30 GeV. Various theoretical predictions are presented, using the same bin widths as the measurement.

agreement between data and predictions can be found in the inclusive and exclusive 1-jet bins, with local p values ranging between 0.1% and 3.6%. Normalizing the total expected cross section to the data results in an improved agreement for these bins, with local p values ranging from 4%–29%.

The combined differential cross sections as a function of p_T^H, $|y^H|$, and p_T^{j1} are shown in Fig. 3 (left). The measured p_T^H and $|y^H|$ distributions are compared to the HRES calculation and the p_T^{j1} measurement is compared to STWZ and JetVHeto predictions. Figure 3 (right) shows the comparisons of the normalized shapes to predictions from the MC event generators NNLOPS, SHERPA 2.1.1, and MG5_aMC@NLO, as well as the HRES calculation. The uncertainties on the predicted shapes are evaluated following the same approach as for the differential cross-section predictions. They are derived from the impact of QCD scale, merging scale, and PDF variations. The mean of the measured p_T^H distribution is 40.1 ± 3.0 GeV, while the means of the MC predictions range from 34 to 37 GeV.

The p values quantifying the compatibility of the measured cross sections and predictions range from 2% to 26%, and for the shapes from 8% to 88%. For the calculation of these values, the theory uncertainties are assumed to be Gaussian distributed and fully correlated between bins [16].

In conclusion, this Letter presents the first measurements of total and differential cross sections and shapes for inclusive $pp \to H$ production. The measurements were performed in the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ channels using the full 2012 data set, which consists of 20.3 fb^{-1} of pp collisions produced by the LHC at a center-of-mass energy of $\sqrt{s} = 8$ TeV and recorded by the ATLAS detector. The results of the two channels are compatible and have similar precision. The measurements indicate that the total production cross section of the Higgs boson is larger, and that it is produced with larger transverse momentum and more associated jets than predicted by the current most advanced SM calculations; however, more data is needed to confirm these observations.

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